Supercontinuum as a light source for miniaturized endoscopes

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Abstract: In this work, we have successfully implemented supercontinuum based illumination through single fiber coupling. The integration of a single fiber illumination with a miniature CMOS sensor forms a very slim and powerful camera module for endoscopic imaging. A set of tests and *in vivo* animal experiments are conducted accordingly to characterize the corresponding illuminance, spectral profile, intensity distribution, and image quality. The key illumination parameters of the supercontinuum, including color rendering index (CRI: 72%~97%) and correlated color temperature (CCT: 3,100K~5,200K), are modified with external filters and compared with those from a LED light source (CRI~76% & CCT~6,500K). The very high spatial coherence of the supercontinuum allows high luminosity conduction through a single multimode fiber (core size~400μm), whose distal end tip is attached with a diffussion tip to broaden the solid angle of illumination (from less than 10° to more than 80°).

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1. Introduction

CMOS sensors has greatly advanced endoscopy and minimally invasive surgery with improved versatility. Finer resolution together with higher sensitivity has enabled better and ever more flexible imaging inside a patient's body, which are further facilitated by the many configurations of CMOS sensors. To take better advantages of imaging CMOS sensors, the corresponding illumination is equally critical. In the last decade, LEDs, with their compactness, long lifetime, high efficiency and high brightness, have gradually replaced halogen and xenon arc lamps in many critical medical illuminations [1, 2]. LED based illumination is often carried out with conventional fiber bundle coupling [3] or directly with miniaturized LED chips packaged in the distal end of a camera module.

However, the emergence of ultra-compact CMOS image sensors, with die size as small as 0.7 x 0.7 mm^2 [4], would call for further innovation in endoscopy illumination so that the footprint of the camera module can fully utilize the ultra-compactness of the CMOS sensors [5–9]. Fiber bundle coupling or packaged LED chips in the distal end, usually of a few millimeters square in size, would be too large for such a purpose. Additionally, direct packaging may present the issue of thermal management [10, 11]. Thus, engineering a very compact light source with high brightness while free of thermal loading is imperative for miniaturized endoscopy.

Supercontinuum, behaving like a laser in spatial coherence while possessing the spectral characteristics like white light LEDs [12, 13], presents as a novel light source that can meet the above demands for endoscopy illumination, while match fittingly to the ultra-compact CMOS [14]. However, the limited field of view (FOV), attributing to the relative small numerical aperture (N.A.) of the coupling fiber, needs to be addressed. Accordingly, we have

engineered a diffusing element which is installed in the distal end of the illuminating fiber to remedy the problems.

In this work, a commercially available supercontinuum light source, which operates at a repetition rate of 78MHz, with CRI up to 97, CCT of 3,100K~5,200K (adjustable by the filters installed), and an illuminance of up to 160,000 lux at 95% of the maximum driving level, is coupled into a multimode fiber for endoscopic illumination. The critical illumination parameters, including CRI, CCT, illuminance, and illumination angle, are characterized and compared with a LED endoscopy light source.

2. Materals and methods

2.1 Supercontinuum coupling

The optical setup for supercontinuum coupling and the corresponding tests are depicked in Fig. 1.
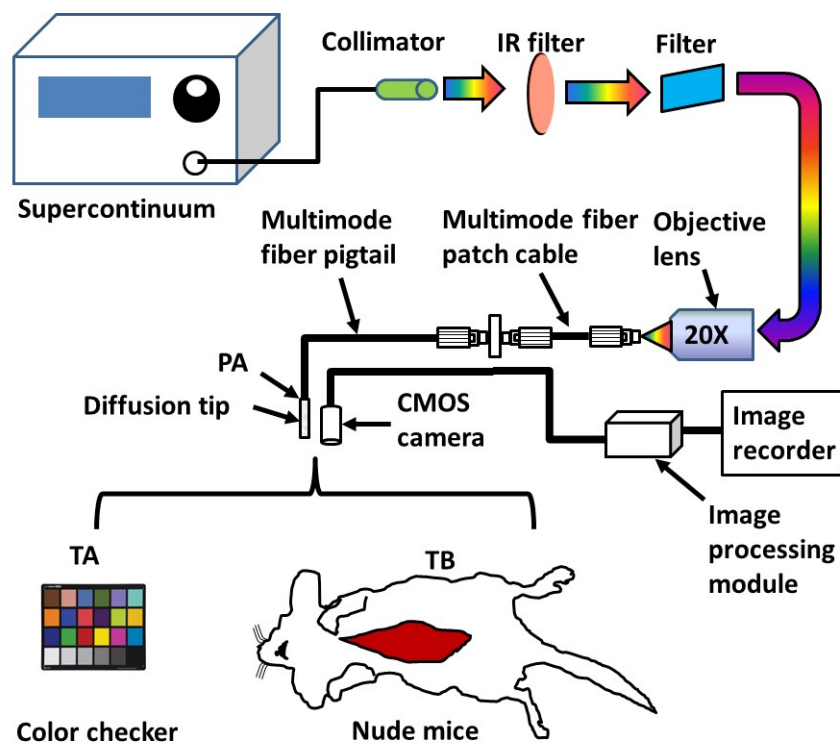

Fig. 1. The schematic on the setup of supercontinuum illumination through fiber coupling. PA is the test point for recording the illuminance, illumination angle, CRI, CCT, and optical power. TA and TB represent the specimen and the experimental animal (nude mice) used for imaging characterization, respectively.

The output of the supercontinuum laser (EXB-6, NKT Photonics A/S, Denmark) is first passed through an IR cut filter (FF01-842/SP-25, Semrock, Inc., USA) to prevent the very high optical power (mostly in the NIR and IR regime) from damaging the optical components in the setup. A 630nm short pass filter (FSR-BG38, Newport Corporation, USA) is then placed after the IR-cut filter to modify the color temperature. The coupling into the multimode patch fiber (M74L, Thorlabs, USA) is completed by an objective lens (RMS20X, Olympus, Japan).

A multimode pigtail fiber (~700μm in outer diameter with a 400μm core) is coupled to the multimode fiber patch cable through a screw-in (fiber-optic connector/physical contact)

adaptor for robust construct so that the pigtail fiber can be easily changed in the case of damage (Fig. 1). The dispersed laser beam exiting the pigtail fiber is then used to illuminate the targeted object. The whole setup is placed in a dark room for testing and high accuracy characterizations, to avoid ambient light interference.

The size of CMOS camera are listed in Table 1. The prototype of miniaturized endoscope assembly has an extra diameter of 1.1 mm added to the outer diameter of the CMOS cameras (Item No.2) [4, 15], taking into account the size of the light conducting fiber and the tube casing. To better characterize the light source, the CMOS camera with higher dynamic range and better resolution(Item No.3) is used.

Table 1. List of information of CMOS camera

Item No.	Part number	Outer diameter(mm)	Resolution (pixel)
1	Q3	0.8	12,000
2	Q7	1.4	76,800
3	FL3-U3-13E4C-C	29 × 29	1,300,000

2.2 Finding the optimal illumination parameters

The repetition rate of the supercontinuum laser is fixed at 78MHz. The output light power and the corresponding spectrum can also be adjusted by tuning the operating current. The unit is set at 95% of the maximum level so that the power is high enough to induce sufficient nonlinear effects in the photonic crystal fiber (PCF) inside the supercontinuum module to allow the extension of the output spectrum well into the blue regime.

The illumination parameters such as CRI, CCT, and illuminance are characterized using the chromameter (SRI2000,Optimum Optoelectronics, Taiwan), which is placed 30mm away from the emission end of the fiber pigtail to match the longest working distance of the CMOS cameras with illumination threshold, denoted as PA in Fig. 1. The corresponding optical power is recorded with the power meter (PM100, Thorlabs Inc., USA). An external endoscopic white light LED lamp (100W, HCM9671, HCM Medica, China) with a fiber bundle cable (active region, Outer Diameter or O.D. of 4mm) is used as a reference, with its power set at maximum.

Figure 2 shows the output spectra of the supercontinuum, with and without the 630nm short pass filter, and the white LED lamp.
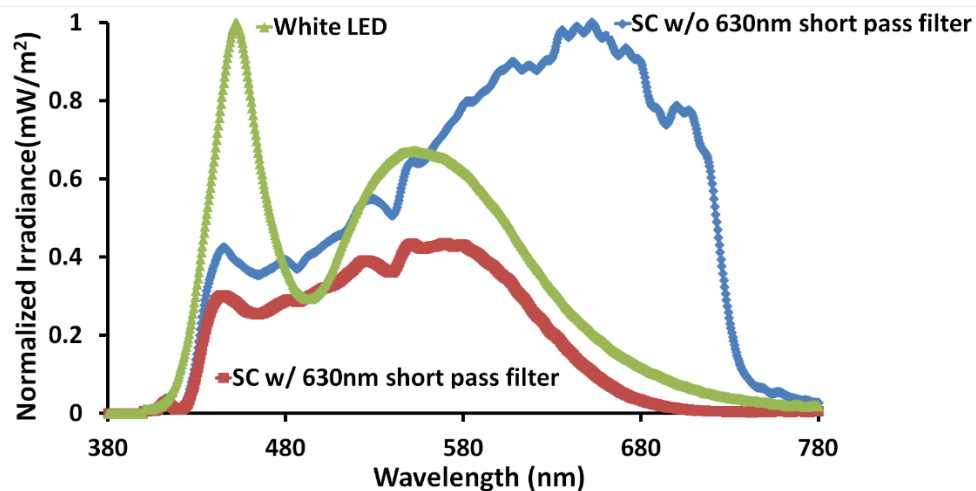

Fig. 2. The spectra of supercontinuum w/ (red line) and w/o (blue line) 630nm short pass filter, and white LED light source (green line).

Figure 2 clearly shows that the unfiltered optical output in the red part of the spectrum (longer than 630nm) is too high for proper illumination and the resulted CCT is too low for good image contrast. Thus, it is necessary to optimize the output spectrum by suppressing the part in red spectrum. A 610nm short pass filter, and a 630nm short pass filter, are then tested. The resulted CCT and CRI of the filtered outputs are listed in Table 2.

Table 2. The CCT and CRI of supercontinuum with different optical filters

Filter	CCT(K)	CRI
610nm short pass filter	6,700	49
630nm short pass filter	5,200	72

The 630nm short pass filter is chosen for the close illumination parameters with LED light source.

The corresponding key illumination characteristics are summarized in Table 3. Table 3 shows that the short pass filter allows color temperature adjustment of supercontinuum to better meet the criteria for medical illumination. Note that the CCT must be between 3,000K and 6,700K according to IEC #60601 [6]. A higher CCT is preferred in endoscopy for sharper image. The threshold of the CMOS camera module is approximately 200 lux. For comparison, the illuminance of white LED after fiber coupling is too low to serve as a viable miniature light source for endoscopic imaging.

Table 3. The color characteristics of supercontinuum (SC) versus white LED

Light sources	SC w/o filter	SC w/ short pass filter	SC w/ filter and diffuser	white LED	White LED through fiber
CRI (± 5)	97	72	70	76	76
CCT(K)	3,100	5,200	5,000	6,500	6,000
Maximum Illuminance(lux)	230,000	160,000	2,700	77,000	230

The very high illuminance of SC directly from the fiber without the use of the diffuser, as shown in Table 3, does not take into account the uniformity of illuminance.

2.3 The quality of illumination

In order to broaden the angle of illumination to match the FOV of the imaging CMOS module, and to improve the uniformity, a light diffusng element is engineered and attached to the emission distal end of the multimode fiber pigtail (PA at Fig. 1). The component is made by mixing either aluminum dioxide powder (1μm in diameter, SA-32, Tyng Hang Industrial Co. Ltd., Taiwan) or optical diffuse powder (2μm in diameter, HSP-200, Sau Inc., Taiwan) with UV (ultraviolet) gel (Norland 61, Norland Products Inc., USA) [16,17]. The ratio (in weight) of the powder to the UV gel is approximately 7%~10%. The semi-solidified mixture is then smeared on the tip for curing. The diameter of the cropped diffusion medium is approximately 1mm and the length is approximately 2mm. Translucent medical tape is used to fix the fiber pigtail near the distal end of the endoscope [18]. The resulted fiber pigtail with the diffusing tip assumes a shape like a matchstick [19].

The diffusion element is also characterized. The luminous intensity distribution curves (LIDC) of the supercontinuum light beam with and without the diffsion element are shown in Fig. 3. The angle of illumination of the supercontinuum light source without the diffusion element is approximately 10° (Fig. 3(a)), which is much less than the FOV of the endoscope. For comparison, the horizontal and the vertical illumination angles with the diffusion element exceed 90° (Fig. 3(b)). Note that the full width at half maximum (FWHM) is used to characterize the illumination angles from the LIDC [16, 17, 20]. In both cases the intensity achieved is greater than the sensitivity threshold of the CMOS camera module. In the case with the diffusuing tip, both the horizontal and vertical angles are much greater than the

FOV(62°) [1] of the CMOS camera used in the successive experiments, indicating the very high effectiveness of the diffusion element.
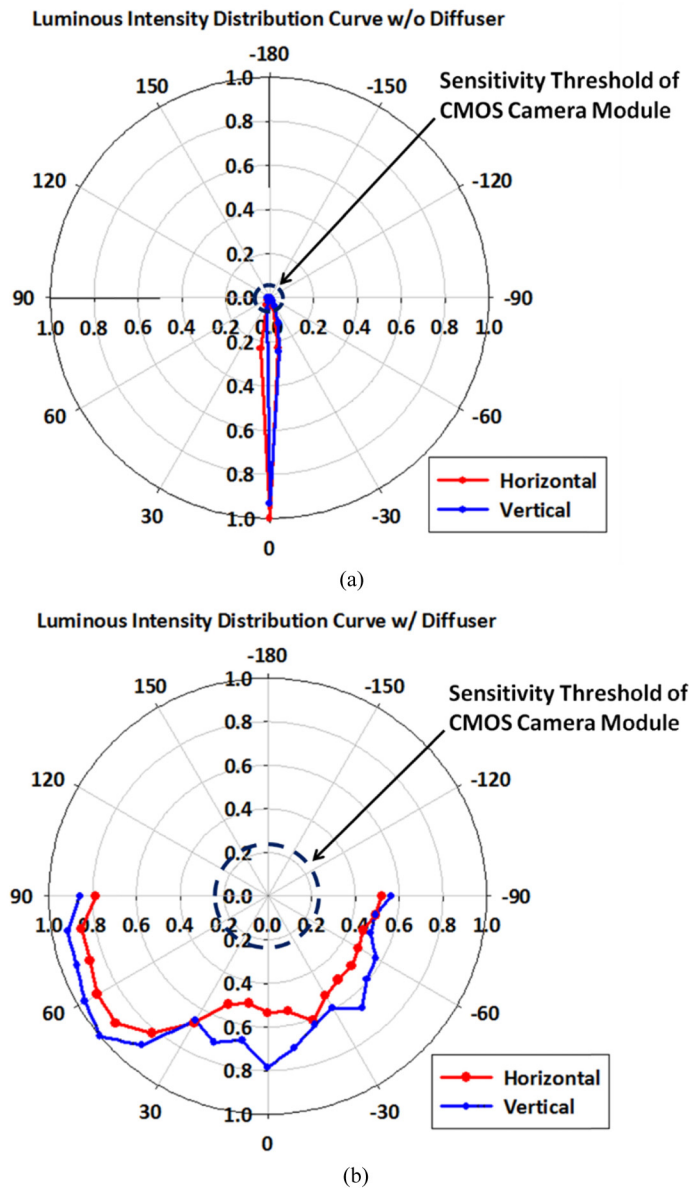

(a)

(b)

Fig. 3. Luminous intensity distribution curves (LIDC) of supercontinuum w/o diffuser (a) and w/ diffuser (b). The red solid line shows the LIDC measured in the horizontal plane while the blue line shows the LIDC in the vertical plane.

The spatial coherence of the supercontinuum is greatly reduced by the diffusion tip. Additionally, the short pass filter further removes the spectral power contributed by the red component with wavelength longer than 630nm and thus reduces the possibility of causing tissue damages due to coherent or thermal effects. Note that there is no specific safety requirement regarding the pulsed (or instantaneous) power level of supercontinuum for endoscopic illumination in IEC #60601.

Nonetheless, the supercontinuum is a class IV pulsed laser before the multimode fiber coupling [21]. Eyewear is used for protection from direct or scattered light during the experiments [22, 23].

3. Results and discussion

A color checker [24] is also used to evaluate the quality of lighting of the supercontinuum laser and the white LED module. The color checker is 25x20 mm in size and is placed 30 mm away from the fiber tip (Fig. 4). 4 illumination conditions are set for comparison, which are (a) supercontinuum without diffuser (b) supercontinuum with diffuser but without filter (c) supercontinuum with both diffuser and short pass filter (d) white LED lamp.

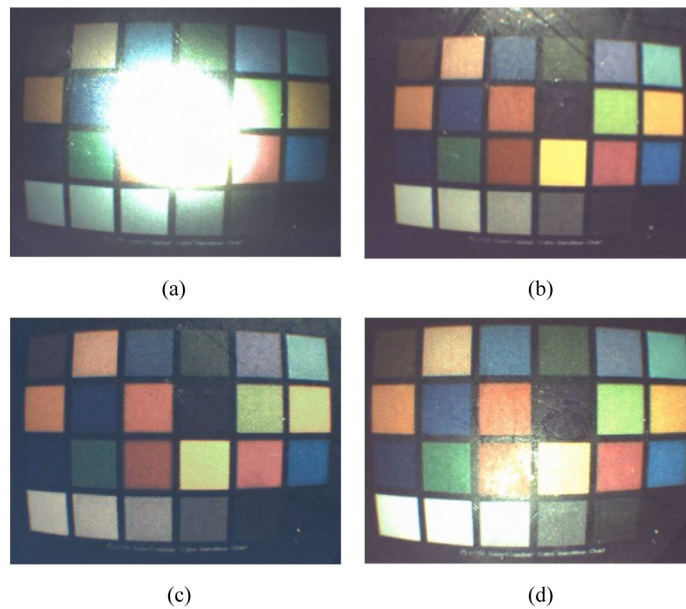(a)   (b)

(c)   (d)

Fig. 4. The images of a color checker under various illumination settings. (a) supercontinuum without the diffuser (b) supercontinuum with the diffuser but without the filter (c) supercontinuum with both the diffuser and the short pass filter (d) white LED lamp.

It is apparemt that the diffuser is necessary to achieve a more uniform illumination. The color and the gray scale is best represented using supercontinuum with both the diffuser and the color filter (Fig. 4(c)).

To emulate the surgical scenario, a 4-month old male nude mice [25] is used as the specimen, indicated as TB in Fig. 1. The illumination conditions for the *in vivo* experiment also follow those used for the color checker. The animal experiment is reviewed and approved by the Institutional Animal Care and Committee of National Yang-Ming University. The male nude mice is placed on the surgical table and laid on its back. Thoracotomy is administered for observing the internal organs. The supercontinuum light source and endoscope camera module assembly is placed approximately 30mm away from the targeted animal for video image recording with alternating illumination settings. The illuminance from the supercontinuum and the LED is kept the same during testing. The videos and images are recorded in MP4(MPEG-4) format. The subject is sacrificed after all measurements. After the experiment, the mice's body is checked and the low average power of the supercontinuum does not cause any detectable effects on the illuminated tissues or organs.

The corresponding imaging using animal model is shown in Fig. 5. In Fig. 5(a), the high brightness of the supercontinuum laser light produces a glaring area within the FOV of the endoscope with dark regions in the lower left corner. For comparison, more uniform lighting

is achieved when the diffusion element is used, as shown in Fig. 5(b) and 5(c). The blood vessels on the surface of the heart can be clearly observed in Fig. 5(b), 5(c), and 5(d). However, the lower CCT due to the more intense red lighting and the elevated response of CMOS sensor toward the red spectrum [26] would obscure the contrast between the blood vessels and the heart (Fig. 5(b)) [27, 28]. The result clearly supports the improvement of image contrast under higher CCT by using the 630nm low pass filter. Illumination using white LED (Fig. 5(d)), w/o coupling through a single fiber, would generate glare and obscure the distinction among various tissues. The mice's heart in Fig. 5(d) appears darker (or bluer), which is attributed to the much higher spectral power in the blue region. As also indicated in Table 3, the illuminance of the multimode fiber coupled white LED is too low to generate a sound image.
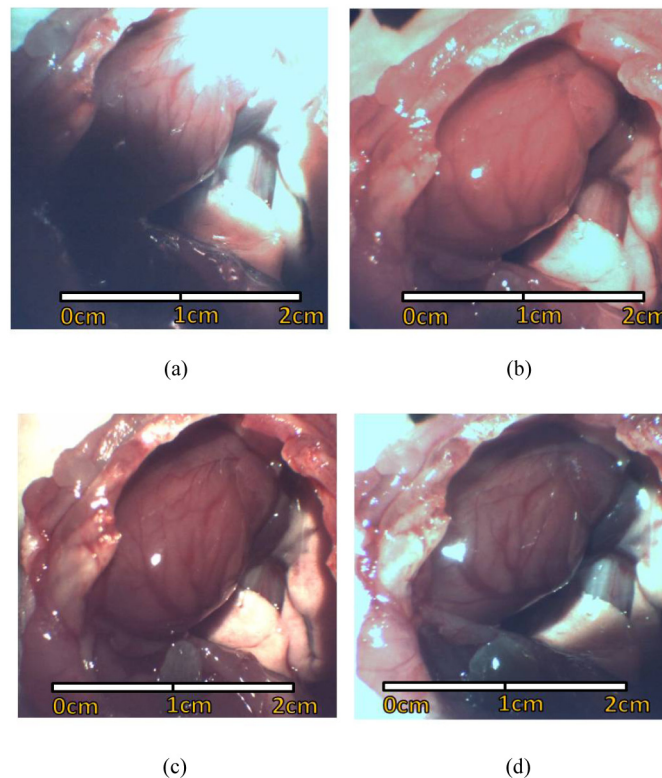

Fig. 5. The nude mice' thoracic cavity illuminated by (a) supercontinuum without diffuser (b) supercontinuum with diffuser but without filter (c) supercontinuum with both diffuser and short pass filter (d) white LED.

White LED has many advantages such as compactness, higher efficiency, and cost effectiveness. However, for restrictive working environments where an endoscope needs to be introduced through narrow passway or tight space, such as bladder and ear drum, the conventional fiber bundle or direct illumination with packaged LED chips will be too big to be effective. For direct illumination with packaged LED chips, the corresponding thermal engineering may not be trivial. The heat generated may considerably raise the thermal noise of the CMOS sensor next to it. Additionally, the spatial coherence of the LED's emission would prevent its effective coupling through a single fiber [10, 12]. As a viable alternative, we have demonstrated the miniaturized combination of supercontinuum with various CMOS image sensors (with die as small as 0.7mm x 0.7mm in size) [4, 15, 29]. The use of a single fiber allows considerable reduction of the footprint on the part of illumination [30, 31]. In this study, packaging of the fiber will increase the size of the bare CMOS camera by

approximately 0.7 mm (~0.4 mm core & cladding plus ~0.3 mm packaging outer layer) in the long diameter. A smaller multimode fiber may be used at the expense of lower supercontinuum coupling efficiency. For endoscopes with overall diameter smaller than 3.0 mm, there is a definite advantage in using a single fiber illumination. The supercontinnum's high spatial coherence and broad spectrum present apparent advantages to be further exploited.

Our results show that supercontinuum can be a high performance light source for miniaturized endoscopes. In recent years, the developments of fiber laser (both CW and pulsed) are progressing rapidly, with ever higher performance and lower cost, similar to how LED develops. Although the cost remains an important issue for practical applications, the corresponding index has reduced from $200/W to $10/W in the last decade [32]. In the future, it is conceivable that fiber laser based supercontinuum will play an ever more prominent role, not just in scientific researches but also in practical applications, including endoscopy.

4. Conclusion

We have successfully demonstrated the feasibility in adopting supercontinnum laser as a light source for endoscopic imaging with miniature camera modules. The CRI, CCT, angle of illumination, and illuminance of supercontinuum have been characterized and compared to phosphor-converted white LED lighting. With the improved uniformity of illuminance brought by the diffuser element, the supercontinuum presents as a versatile light source ideally suited to work with the miniaturized CMOS image sensors in forming an ultra-slim endoscopic system for diagnosis and minimally invasive surgery. This unique capacity promise unprecedented opportunities in which the existing video endoscope is not feasible due to size limitations of light guide cable.